The EUCAMS gear partnership – a model of industry/academic collaboration

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Abstract

Challenges in maintenance systems can pose multi-faceted problems, which are difficult to resolve alone. Over a four year period, a partnership evolved a vision for tackling the understanding of fundamentally difficult mechanical failures and their detection, with potential for practical exploitation of the solutions. The partnership assembled a team of researchers and far-sighted project management, to undertake a study of gearbox failures, including finite element modelling, gear testing, and signal analysis. The partnership trained a series of doctoral and postdoctoral staff in running an integrated project, coping with changes in staffing and locations. The final stages of the work will validate the models and signal processing.

1. Introduction

This paper is about how partnerships help solve problems, and it is illustrated with an integrated case study in gear damage detection. Through-life systems sustainment requires a fusion of innovative management and technology, but this is rarely achieved by a single, monolithic organisation, and certainly requires a wide range of skills. The funding for the resources to solve technical problems arises from a range of sources, and distinct advantages arise from the exploitation of match funding and complementary project opportunities.

The Ministry of Defence Engine Usage, Condition Monitoring and Management Systems (EUCAMS) supports the improvement of availability, sustainability, affordability and airworthiness by enabling intelligent propulsion system management [(1)]. The strategy includes legacy and future aircraft, as well as Unmanned Air Vehicles (UAV). A whole life approach is adopted, where the in-service support requirements are defined by the Defence Logistic Organisation (DLO). The EUCAMS steering committee includes stakeholders such as the MOD Material Integrity Group (MIG) and the Defence Science and Technology Laboratory (DSTL). The goal is to "improve availability, sustainability, affordability and airworthiness by enabling intelligent propulsion system management" [(1)].

The technology acquisition strategy of EUCAMS is to invest in a broad range of generic technologies (usually up to Technology Readiness Level (TRL) 7). The aims are:

- intelligent system health management;
- provide expertise on methods and technologies;
- access to technology through collaboration.

One area of focus is gearbox technology. Current strategies are effective at preventing failures in military aircraft, but monitoring is expensive, and the number of gearboxes is considerable. All helicopters use several complex gearboxes; turbo prop engines include gearboxes; and importantly, the new Joint Strike Fighter (JSF) short take-off and vertical landing (STOVL) variant includes a lift fan gearbox. Commercial versions of aircraft, for example helicopters, have demonstrated recent catastrophic failures, under maintenance regimes which are certified and believed to be sound. Monitoring systems are not entirely effective for detecting failures in gears. In particular, light aerospace gears have an occasional mode of failure which involves deep fatigue cracking of the gear body, which is potentially much more hazardous than surface wear or tooth loss. The partnership has focussed on this fault mode.

The EUCAMS partnership also contributes to a wider North Atlantic Treaty Organisation (NATO) advanced vehicle technology programme. The US and UK partners collaborate on a wide range of topics, including airframe, propulsion, sensing and system management, for example gas turbine engine test cell instrumentation [(2)]. The field is also represented by a pan-European virtual institute for work to support sector-wide goals [(3)].

The NATO partnership aims to progress the technology available to its allies by a structured programme of research, development and dissemination. It involves partners from military and non-military organisations, working jointly and often voluntarily on strategic topics. Gear boxes are an important part of the power train of a number of fixed-wing and rotating wing platforms, which pose significantly challenges now and in the future. The advanced vehicle technology programme relies on a broad range of partners on both sides of the Atlantic to deliver its strategic goals.

The paper will describe the partnership, its structure and objective. It will continue to describe the work in progress, and the benefits to the partners, before drawing conclusions.

2. Partnership

The UK Ministry of Defence has a commitment to the strategic acquisition of capabilities, including novel diagnostic and prognostic technologies. A long term relationship with QinetiQ has led to a deep rooted understanding of the culture, as well as technical requirements, and hence a well developed relationship for service and support. One of the important areas of development is the building of new partnerships to help to understand, and to fill, gaps in the strategic tool-kit for logistics support.

The selection of new partners, particularly where novel technologies are involved, is a choice which involves a combination of expertise, access to additional funding, culture, and a commitment to a long-term working relationship. The combination of expertise has involved many minds applied to problem situations, which leads to creative solutions. The partnership aims not only to solve technical problems, but also to educate young people and to disseminate its findings. An important part of the formation of the partnership was the ability to bring additional resource. As part of the Ministry of Defence strategy, a small research fund has been available as seed-corn for projects. But this was substantially boosted by sponsoring university programmes, which introduced EPSRC research training grants from Manchester and Warwick universities. These grants directly funded doctoral researchers, working full time on the programme. Both researchers spent extended periods working at a QinetiQ site, in order to become fully embedded in the team’s culture.

The longevity of the relationship is important to manage. Partnerships experience the development of new staff capabilities; changes of personnel; changes in focus; and changes in careers and locations. But the long term impact requires a steady and flexible project management process. Figure 1 illustrates the relationship between the partners. The majority of the partners meet quarterly, circulating between host companies and institutions. QinetiQ reports directly to the Ministry of Defence.

3. Objective

The objective of the work programme is to understand the signals derived at the outside of a gearbox assembly, arising from a fatigue crack in a gear. The programme will compare the predicted outputs from a numerical model with the measured outputs from a series of validation tests, in order to increase the confidence in predictive health monitoring.

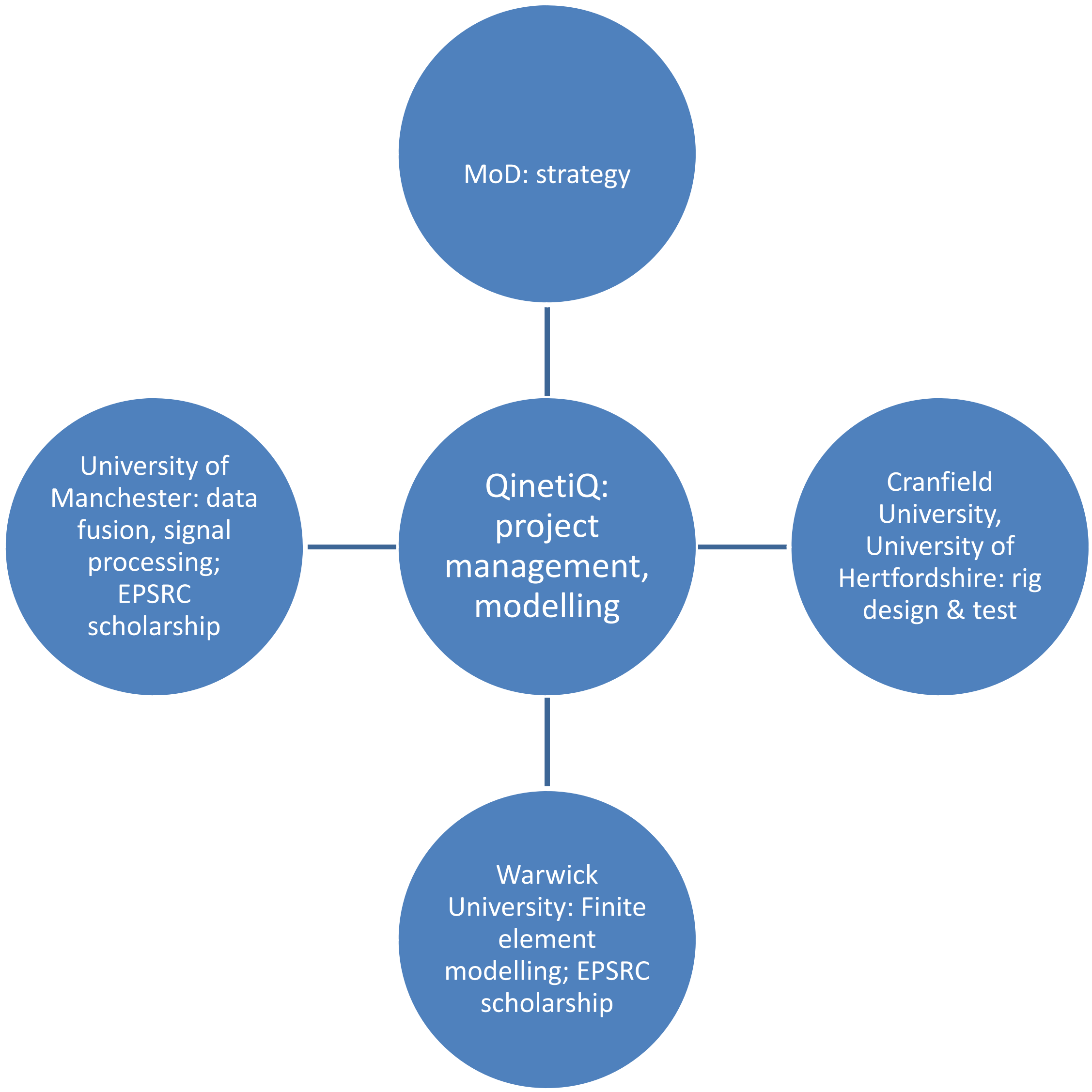
MoD: strategy
University of Manchester: data fusion, signal processing; EPSRC scholarship
QinetiQ: project management, modelling
Cranfield University, University of Hertfordshire: rig design & test
Warwick University: Finite element modelling; EPSRC scholarship

Figure 1: Structural diagram describing the partnership and responsibilities

4. Work programme

The partners have defined four parallel work packages which are summarised as follows:

- project management and overall modelling design (QinetiQ);
- detailed 3-dimensional numerical modelling (Warwick);
- signal processing and data fusion for prognosis (Manchester);
- rig design, build and test programme (Hertfordshire, Cranfield).

4.1 Project management and overall modelling design

The project management package and client liaison is led by QinetiQ, along with an overall view of the modelling and test validation programme. As described above, the project management works well because of the flexibility accepted in coping with a multi-partner project with multiple funding sources, and the longevity arising from the tolerance of staff and location changes.

4.2 3-dimensional numerical modelling

The modelling is focussed at the University of Warwick. The aim is to produce a method which predicts the behaviour of 3 dimensional crack geometry in gear structures during the dynamic loading and unloading process as the affected teeth pass through the mesh, and to modulate the resulting signals as they pass through a model of the structure including shafts, bearings and supporting fabrications. The signals will then be used to predict the behaviour of real systems, and the model will be tuned by validation against experimental data. The work, which is supported by an EPSRC CASE award, extends research in powertrain gear transmission error prediction using non-linear finite element methods, and gear tooth contact analysis for the reduction of fatigue wear [4,5].

4.3 Signal processing and data fusion for prognosis

Work on prognosis is focussed at the University of Manchester, with emphasis on signal processing and data fusion. With a review of existing helicopter usage and monitoring systems (HUMS), the work aims to improve on the well established statistical methods to form a more robust prognosis [6]. It is important to note that the partnership's work hinges on the occasional failure of HUMS to detect gear cracking. The work, which is supported by an EPSRC EngD award, builds on previous research in gear degradation, and analysis based on data fusion [7,8].

The strategy for the signal processing is to use automated procedures which combine knowledge as well as data. Procedures which use bulk statistical analyses have been fairly effective, but refinements are necessary to avoid missed alarms. The fourth order techniques (modified kurtosis methods) are good for automation but susceptible to diminution of sensitivity after the initial detection. A particular aim is a monotonic progression of the indicator, so that the alarm is not diminished at any time [5].

4.4 Rig development and instrumentation

One of the main aims of the rig research was to achieve root failure fatigue on gears. A review on gear fatigue literature was initially made and causes of this failure were determined. It was concluded that misalignment in gears, initiated by their mounting shafts, is the prime cause [9,10]. It was also considered that a rig which can provide controlled misalignment gear testing is commercially unavailable. This reason led to a decision for developing a customized gear testing facility.

The gear testing facility was designed, developed and commissioned at University of Hertfordshire – and has recently moved to Cranfield University. The key elements of the facility including shafts, base structure, tools for misalignment control and couplings, were designed and then modelled in CATIA©. The other main elements including the motor, dynamometer, coolant and lubricant pumps, and power controllers were selected and purchased from commercial vendors.

Local manufacturers were used for the rig component manufacturing. Once the parts were manufactured, the rig assembly took place in-house. During assembly, rig instrumentation was also considered. The instrumentation installed in this process includes vibration accelerometers, acoustic emissions sensors, displacement probes and optical rotary encoders. All of them were used to provide real time information for gear root fatigue on a computer display, with data acquisition through a modular package from National Instruments.

The completed rig is shown in Figure 2, without its guarding and alignment plates, for clarity.

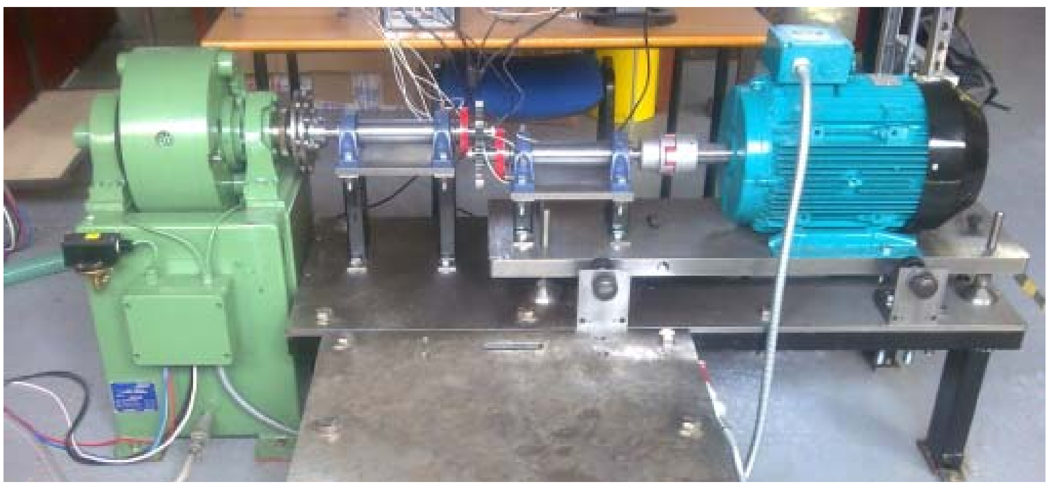

Figure 2: A view of rig main components after assembly

5. Benefits to the partners

The partners have contributed effort from several directions, to meet a common goal, but have benefited in a range of ways. Fundamentally, the improvement in understanding and the prevention of future catastrophic failures, is the key benefit, which will eventually avoid massive cost and more significantly, loss of life. However, the intermediate, and less extraordinary, results of the programme have achieved a series of valuable and tangible benefits:

- improved understanding for four organisations with involvement of at least 12 specialists;
- contribution to the NATO strategic goals for advanced vehicle technologies;
- training for three young people in doctoral and post-doctoral research methods;
- research and development of new scientific knowledge in the context of industrial applications requirements;
- dissemination of knowledge through a series of articles, presentation at international conferences, and web sites;

- a lasting physical resource, in the form of a test rig which will see use in further experimental programmes.

6. Conclusion

Working with a partnership allows a critical mass of expertise to be assembled. This allows a considered approach to a difficult, integrated problem, by combining the talents of several complementary organisations, and drawing on the different thinking processes. Clearly there is no monopoly on good ideas, or a single solution which fits all problems.

The partnership has made significant strides towards its technical objective by a concerted effort of planning and execution. The resources were assembled from several sources, and required mutual agreement to determine their focus and tasks. This was achieved by an understanding of each partner's measureable outcomes, whether industrial or academic. The combination of several funded projects allowed a synergy which achieved more than the sum of the parts.

Several changes occurred throughout the programme, as people adopted new roles. The partnership was robust enough to deal with departures, newcomers and role changes – even the rig has moved. The shared expertise supported such change by fully briefing new members of the team. The good relationship fostered early in the partnership allowed smooth change

Further work will be undertaken to produce data sets for validation of the modelling and signal processing techniques, running gears to failure in a range of scenarios. The partnership has interests in further projects and collaborations in the UK and internationally.

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References

1. Stuart Driver, Mark Robinson, Ed Moses, Hesham Azzam, Jonathan Cook, Peter Knight, 2007, The UK MOD EUCAMS Strategy and The FUMS^{TM} Developments, http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04161666
2. NATO Research and Technology Organisation, Applied Vehicle Technology (AVT) technical panel AVT-180 Gas Turbine Engine Test Cell Instrumentation http://www.rta.nato.int/panel.asp?panel=AVT , last accessed January 2011
3. European Virtual Institute for Gas Turbine Instrumentation http://www.evi-gti.com/index.php, last accessed January 2011

4. K. Mao, ‘An Approach for Powertrain Gear Transmission Error Prediction Using Non-linear Finite Element Method’, IMechE - Journal of Automobile Engineering, Vol. 220 Issue 10, pp1455-1463, 2006,
5. K. Mao, ‘Gear Tooth Contact Analysis and Its Application in the Reduction of Fatigue Wear’, Wear, 262, pp1281-1288, 2007.
6. P.J. Rzeszucinski, J. Sinha, R. Edwards, A. Starr, 2011, A New Technique for Condition Monitoring of Helicopter Gearboxes, International Conference on Vibration Problems
7. Khan M A, Starr A G, Cooper, D, 2009, BS-ISO helical gear fatigue life estimation and wear quantitative features analysis, Strain International Journal of Experimental Mechanics 45 (4) pp.358-363 DOI: 10.1111/j.1475-1305.2008.00457.x
8. Esteban J, Starr A G, Willetts R, Hannah P, Bryanston-Cross P, 2005, A review of data fusion models and architectures: towards engineering guidelines, Neural Computing & Applications Springer-Verlag London Ltd, ISSN: 0941-0643, Volume 14, Number 4, pp273 – 281
9. Breen, D. H., 1990, Fundamentals of Gear/Strength relationship; Materials. Gear Design AE15, Warendale, PA USA, SAE International
10. Collins, J. A., 2003, Mechanical design of machine elements and machines. New York, John Wiley & Sons.

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